IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re/ Haim H. Bau
Application No. 10/657,302
Filed: September 8, 2003
Confirmation No. 9721

Examiner: Michael Koczo, Jr.
Art Unit 3746

CONTROLLED MAGNETOHYDRODYNAMIC FLUIDIC NETWORKS AND STIRRERS

(Attorney Docket No. P27,076-A USA)

DECLARATION UNDER 37 C.F.R. § 1.131

I, Haim H. Bau, declare as follows:

1. I am the applicant of the above-identified patent application, the inventor of the subject matter described and claimed therein, and a Professor of Mechanical Engineering and Applied Mechanics at the School of Engineering & Applied Science of the University of Pennsylvania ("Penn").

2. In accordance with Penn's patent policies, Penn employees who seek patent protection for their inventions are obligated to disclose such inventions to the Center for Technology Transfer ("CTT"), the office at Penn responsible for evaluating inventions and filing patent applications on behalf of Penn employees. If CTT chooses not to pursue patent protection for a given invention, the patent policies provide for the return of the invention to the inventor so that the inventor may file a patent application on his or her own.

2. Prior to January 1, 2002, I had completed my invention as described and claimed in the subject application in this country, as evidenced by the following:

a. Prior to January 1, 2002, I submitted an invention disclosure to the CTT in accordance with my obligations under Penn's patent policies. A true and correct copy of the cover letter and invention disclosure is attached as Exhibit A.

b. The invention disclosure was evaluated by CTT and, based on such evaluation, CTT returned the invention to me in or about August or early September of 2002.

c. Upon the return of the invention to me, I proceeded to seek patent protection by preparing a provisional patent application which was filed on September 9, 2002.

Dated: September 4, 2007

Haim H. Bau

Haim H. Bau

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Center for Technology Transfer
3700 Market Street, Suite 300
Philadelphia, PA 19104

Re: Invention Disclosure: Electro Magnetic Pumping and Stirring in Microfluidic Systems

Dear Sir/Madam,

Enclosed please find an invention disclosure describing the use of electromagnetic forces to manipulate electrically conducting liquids in microdevices. Many biological liquids contain ions and therefore conduct electricity. Although the use of electromagnetic forces to manipulate fluids is not new, I have not seen these ideas applied in the realm of microdevices. In particular, I believe that the proposed electromagnetic stirrer/mixer is novel. I did not conduct, however, a search of the patent literature.

I am filing this disclosure at a relatively early stage of our research because we are readying a paper for publication and because recently, due to slow action, we may have missed out on important opportunities.

If the university decides not to file a patent within a reasonable amount of time, say 6 months, I would like the invention to be returned to me so that I can pursue patenting it on my own.

Sincerely,

Haim H. Bau

Haim H. Bau

(2) Re Motorola's Disclosure

UNIVERSITY OF PENNSYLVANIA

P IMINARY TECHNOLOGY DISCLOSURE RM

PLEASE SEE REVERSE SIDE FOR INSTRUCTIONS

Date Submitted ______________

1. **Disclosure Title.** ELECROMAGNETIC PUMPING & STIRRING IN MICROFLUIDIC SYSTEMS

2. **Relation to Previous Disclosure:** Yes ____ No ✓ If Yes, file number and title: ______________

3. **Possible Obligations to Others:**

   Funding:
   NIH/Government ✓ Grant #: ______________ Corporate or Other ______ Sponsor Name DARPA

   Related Agreements:
   ___ Sponsored Research Agreements ___ Material Transfer Agreements
   ___ Collaborative Agreements ___ Inter-Institutional Agreements

   Other Parties (Include name/phone #, organization) NONE

   Materials:
   Did you use any material obtained from another party in developing this technology? Yes ____ No ✓ Source ______________

4. **Critical Dates:**

	Circle One:	Date:	Describe:
-- Disclosure or presentation to others?	No Yes	______	Who/Affiliation? Government
-- Submitted as an abstract or manuscript?	No Yes	______	Expected Publication? ______
-- Submitted in grant application or report?	No Yes	______	Expected Funding? ______
-- Published in any form - including internet?	No Yes	______	Where Published? ______

Please include a copy of any such abstracts, manuscripts or grants with your Form.

5. **Commercialization:**

What products, processes or services would result from your technology? Microfluidic systems, labs on a chip

Do you know of (please provide names and contact information if possible):

Colleagues working in complimentary areas? ______________

Companies that might be interested in licensing your technology? ______________

6. **Contributors:** I/We hereby submit this in accordance with University policies:

Signature(s)	Name (print)	Citizenship	School & Dept (or Institution if not Penn)	Phone #	Email
[signature] [Primary Contact]	HAIM H. BAU	USA	SEAS/MEAM	215-898-8363	bau@seas.upenn.edu

7. **Description of Technology: (VERY IMPORTANT) CTT cannot assess the protectability, technical merit and commercial potential of your disclosure without this information.**

N2435
TPF

Please provide in hard copy and on electronic disk (IBM), if possible.

1) Grant applications and manuscripts describing the technology (as above).
2) Curriculum vitae (CV) of inventor(s).
3) Related publications and patents by you and others working in this field.
4) A concise description of the technology (2-5 pages), including the following:
   - ✓ a) Brief Summary
   - b) Stage of Development (Are there any problems with your present technology? Is there a need for additional funding, time, etc?)
   - c) Applications/Commercial use of the technology/Products or services envisioned
   - d) Closest known similar technology or competing products
   - e) Differences and advantages over other technology or products.

RECEIVED

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CENTER FOR TECHNOLOGY TRANSFER

Electro Magnetic Manipulation of Fluids in Microfluidic Systems

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Dept. Mechanical Engineering and Applied Mechanics
University of Pennsylvania

In recent years, there has been a rapidly growing interest in developing minute chemical and biological laboratories and reactors. Often it is necessary to move fluids from one part of a device to another, control the fluid motion, and mix and separate fluids. In microdevices, these tasks are far from trivial. It is difficult to integrate pumps capable of generating high pressures in these systems. Typically, electrostatic forces are being used to move liquids around. These forces usually can induce only very low flow-rates, require the use of very high electrical potentials, and may cause significant heating of the solution. The use of electromagnetic (EM) forces presents an interesting means for manipulating liquids in micro fluidic devices. The only requirement is that the liquid be at least slightly conductive. This requirement is met by many biological solutions. The use of EM forces offers much greater flexibility than the use of electrostatic forces alone and this with less undesirable side effects. The use of EM forces to induce and manipulate fluid flow is not new. The field is commonly known as magneto-hydro-dynamics (MHD). Typically, MHD is associated with high conductivity fluids such as liquid metals and ionized gases. The small length scales prevalent in microfluidic devices make the use of EM forces in microdevices and slightly conductive liquids practical. It appears that EM has not, however, been implemented thus far in MEMS. The first part of the invention describes the use of EM to pump and move fluids. This is merely an implementation of well-known concept in a micro-device. We demonstrated the concept in preliminary experiments. The second part of the invention describes the use of EM to stir and mix fluids. Stirring and mixing is an essential but difficult task in microdevices because it is difficult to introduce moving components into the device. Moreover, the fluid tends to flow at very low speeds (low Reynolds number) so that turbulence is not available to assist in the mixing process. I believe that the stirrer/mixer idea is novel. An obvious extension of these ideas is for the control of liquid flow in microdevices. Finally, electromagnetic fields can be used for the separation and identification of macromolecules. This last idea has not been evaluated in any quantitative way and should be regarded as speculative.

The ideas described herein can be implemented in any substrate material such a silicon, plastics, polymers, and ceramics. A particularly simple and convenient implementation can be achieved by using layered manufacturing and co-fired ceramic tapes. In fact, the prototypes that we have fabricated thus far were made with low temperature co-fired ceramic tapes. The electrodes needed for the production of the electric fields can be printed (using screen-printing or jet printers), vapor deposited, or shaped by photolithographic means. Permanent magnets and/or induction coils can be used to generate the required magnetic fields. In the latter case, the intensity of the magnetic field can be increased and controlled through the use of soft magnetic materials. Coils and soft magnets can be readily integrated into structures made in multi-layered ceramic tapes. In prior work, our group has demonstrated the ability to do so. Since this technology is described in a number of papers generated by our group, I will not repeat the description here in any details.

1. ELECTROMAGNETIC PUMPING

In microdevices, one often uses electric fields to induce electrophoretic flows. This often requires high voltage, and the resulting fluid velocities are typically very low. An undesirable side effect is heat generation in the solution. Electromagnetic pumping presents an interesting alternative that may facilitate much higher flow rates than would be possible with electrostatic fields alone. All that is required is that the fluid be slightly electrically conducting. In many cases, biological liquids contain ions and conduct electricity. Electromagnetic (EM) pumping is not a new idea. Electromagnetic pumping has been considered for applications ranging from submarine propulsion to fission energy generation. It seems, however, that electromagnetic pumping has not been implemented thus far in microdevices.

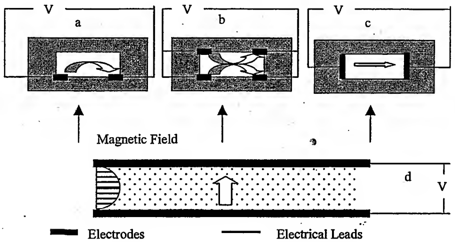
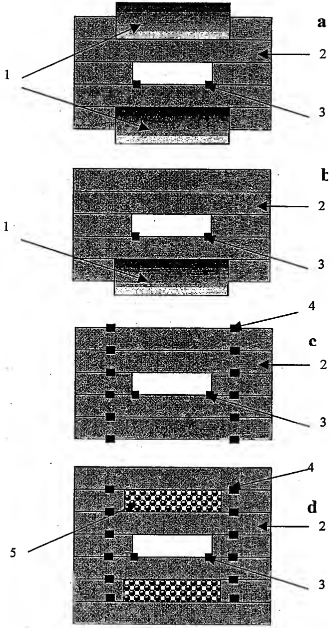


Fig. 1: Figs 1a, b, and c depict the conduit's cross-section that is transverse to the direction of the flow. The conduits are either fully filled with liquid or contain a drop (slug) of liquid. The magnetic field is directed upwards and the electric current is depicted schematically with arrows. Fig. 1d depicts a view from above. The magnetic field is directed towards the viewer. In the top view, three different embodiments of electrodes are shown (heavy dark lines). As a result of the interaction between the magnetic and electric fields, fluid motion is induced from left to right in Fig. 1d.

The interaction between the magnetic and electric fields results in a body (Lorentz) force that propels the liquid. By proper adjustment of the electric and magnetic fields, one can achieve fairly large forces. The use of EM forces allows us to compensate for low electric fields by increasing the strength of the magnetic field. The only practical limitation is that in aqueous solutions and in the presence of high electric currents, one experiences significant hydrogen bubble generation that may impede device operation. The same problem, perhaps even to a larger extent, also exists in electrostatically driven flows. The EM field can be used to propel either drops (slugs) of liquid or to induce motion in a conduit fully filled with liquid. In our experiments, we demonstrated the propulsion of a mercury slug and the motion of water in a water-filled conduit.



The electromagnetic drive can be easily implemented in microdevices fabricated in a variety of materials. It is particularly easy to implement the electromagnetic drive in devices fabricated in low temperature co-fired ceramic tapes. In fact, we used low temperature co-fired ceramic tapes to construct our prototypes. Fig. 1 depicts schematically a few possible embodiments of the electromagnetic pump. The pumps consist of electrodes typically positioned in a direction parallel to the desired flow direction. There are very many possible arrangements of the electrodes. Since typically one forms the electrodes by thick film printing or photolithography, very complex electrode shapes are possible. Fig. 1 depicts just a few possibilities. The magnetic field is imposed in the indicated direction in Fig. 1. There are very many ways of inducing the magnetic field - some of which are described in Fig. 2.

Figs. 1a, b, and c depict the conduit's cross section that is transverse to the flow direction. The conduits are either filled with liquid or contain a liquid drop (slug). Fig. 1d depicts a top view of the flow conduit. Electrodes are shaped along the right and left sides of the conduit. The electrodes can be shaped along the two bottom corners alone (Fig. 1a); along all four corners

Fig. 2: Various ways of generating the magnetic fields. (1) permanent magnet or poles of an external electromagnet; (2) layers of co-fired ceramic tapes; (3) electrodes; (4) conductors forming coils for the generation of an electromagnetic field; and (5) inclusions of soft magnetic material or tapes consisting of magnetic oxide particles.

Figs. 2 a and 2b depict the generation of the magnetic field through the use of one or two permanent magnets. Figs. 2c and 2d depict the generation of a magnetic field through the use of coils. Fig. 2d also shows inclusions of soft magnetic material.

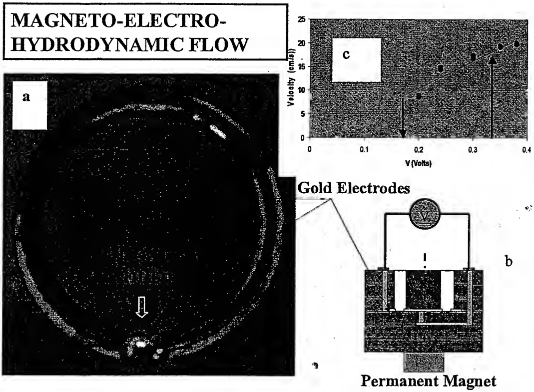


Fig. 3: (a) Top view of the toroidal flow conduit. The yellow lines show the gold electrodes. Also shown is the mercury slug. (b) A cross-section of the conduit. (c) A sample of results: the mercury velocity is depicted as a function of the voltage. The mercury was propelled around the torus.

(Fig. 1b); along the entire faces of the right and left walls (Fig. 1 d); or along any part of the left and right, side walls. The arrangement depicted in Fig. 1a was used in our experiments. Electrodes positioned on opposing walls are subjected to a potential difference. This potential difference induces current flow in the liquid that is shown schematically by arrows in Fig. 1.

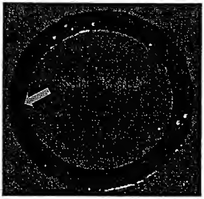


Fig. 4: The conduit is filled with saline solution. EM forces were used to induce fluid motion and propel the fluid around the torus.

To induce the magnetic field, one may use either permanent magnets or coils carrying electric current or any combination thereof. Fig. 2 depicts just a few possibilities. The intensity of electromagnetic fields carrying currents can be directed and enhanced through the use of soft magnets. Soft magnets can be integrated into the ceramic tape system by embedding soft magnetic materials in cavities formed in the ceramic tapes, by plating surfaces with magnetic materials such as permalloy or by preparing tape formulations from magnetic oxides.

To demonstrate the feasibility of electromagnetic pumping, we constructed a test device with low temperature co-fired tapes. See Fig. 3. The test device consisted of a conduit in the shape of a torus. Electrodes were printed at the conduit's corners (see the cross-section at the right bottom corner). The magnetic field was provided by a permanent magnet.

Experiments were conducted in both an open and closed conduits. The closed conduit was capped with a glass cover. The experiments were carried out with both a slug of mercury (Fig. 3) and with slightly saline water (Fig. 4). In the case of the mercury slug, we propelled the mercury at relatively high speeds on the order of 0.1m/s, in effect constructing an electromagnetic motor. In the case of the water experiments, we were also able to propel the fluid at fairly high flow rates. The only limitation on how fast we could go was the generation of hydrogen bubbles that were trapped in the closed conduit. One can still achieve high flow rates with water by reducing the current and compensating by increasing the intensity of the magnetic field.

2. FLUID MIXING

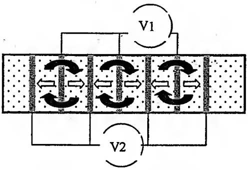


Fig. 5: A minute magneto hydrodynamic mixture. The Lorentz forces induce circulation in the fluid.

Often, in order to facilitate chemical and biological reactions, one needs to mix various reagents and chemicals. Although the characteristic lengths associated with micro-devices are small, typically on the order of 100μm, in the case of large molecules, diffusion alone does not provide a sufficiently rapid means for mixing. For example, at room temperature, myosin's coefficient of diffusion in water is about $10^{-11}m^2/s$, and the time constant for diffusion along a length of 100μm is intolerably large-10^3s. Commonly, one encounters only low Reynolds number flows in micro devices, and turbulence is not available to enhance mixing. Moreover, often it is not feasible to incorporate moving components such as stirrers into microdevices. Thus, one is forced to look for alternatives in order to make the mixing process more efficient.

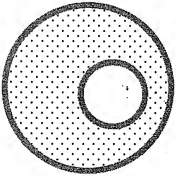


Fig. 6: A schematic description of an electromagnetic mixer shaped in the form of an eccentric annulus.

It is proposed to use electromagnetic forces to induce fluid motion. The electromagnetically-induced motions can be used both to enhance mixing and to reduce temperature gradients. This concept is different from the magnetic bars that are often used as stirrers. The basic idea is explained in Fig. 5. Consider a cavity filled with the fluid to be stirred. Electrodes are printed or deposited transversely along the length of the cavity. A magnetic field is imposed in the direction perpendicular to the paper. The magnetic field can be generated either by a permanent magnet or by multilayers of coils printed in ceramic tapes. In the latter case, the magnetic field may be enhanced by embedding soft magnetic material in the tapes. The electrodes are subjected alternately to two different potentials, V1 and V2. As a result of the potential difference, current (shown as white, horizontal arrows) is induced in the fluid. The electric current and the magnetic field combine to form a Lorentz force that is directed in the y-direction. As the result, fluid motion is induced. Since the fluid is confined, the net effect will be the generation of cellular

convection as indicated by the heavy, curved arrows. This motion is likely to stretch material interfaces, stir the fluid, and enhance mixing. Furthermore, by changing the polarity of the electrode, the direction of the fluid motion can be reversed. The electrode's polarity can be changed periodically (or aperiodically) to form time-dependent flow (possibly chaotic flow) and enhance mixing even further.

The embodiment described in Fig. 5 is just one example of many possibilities. Since by using screen-printing or photolithography, we are able to shape the electrodes in any imaginable pattern, one can envision the formation of very complicated flows indeed. As another example, consider the mixture depicted in Fig. 6. The device consists of two electrodes each having a shape of a circle. The magnetic field is perpendicular to the plane of the paper. As a result of a potential difference across these two electrodes, angular fluid motion is induced. By periodically alternating the potential difference across the electrodes, one can induce extremely complicated fluid motions. Indeed, macroscopic devices like the one depicted in Fig. 6 serve as a paradigm of chaotic advection. In contrast to our device, in the macroscopic devices, fluid motion is induced by rotating the bounding cylinders. Moving cylinders are very difficult to implement on the micro-scale.

As yet another manifestation of similar ideas, one can envision shrinking the size of the inner cylinder to almost a dot. In this case, the induced fluid motion will be in the form of a vortex filament. The direction of the vortex can be alternated by alternating the direction of the electrodes' potential or the magnetic field. A number of vortices may interact with each other to form extremely complicated flow patterns.

3. FLOW CONTROL

Clearly the ability to induce forces in the fluid when and where they are needed can be used to effectuate flow control. In lieu of using valves, one can divert the fluid to go in a desired path by appropriate manipulation of electromagnetic forces.